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The metallicity properties of long-GRB hosts

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Abstract. The recently-discovered Fundamental Metallicity Relation (FMR), which is the tight dependence of metallicity on both mass and SFR, proves to be a very useful tool to study the metallicity properties of various classes of galaxies. We have used the FMR to study the galaxies hosting long-GRBs. While the GRB hosts have lower metallicities than typical galaxies of the same mass, i.e., they are below the mass-metallicity relation, they are fully consistent with the FMR. This shows that the difference with the mass-metallicity relation is due to higher than average SFRs, and that GRBs with optical afterglows do not preferentially select low-metallicity hosts among the star-forming galaxies.

Key words. Gamma-ray burst: general – Galaxies: abundances

1. Introduction

The gas-phase chemical abundance in galaxies is influenced by several effects: star formation and evolution, which reduce the amount of gas and increase the amount of metals, infall of metal-poor gas from the outer part of the galaxy and from the intergalactic medium, and outflow of enriched material due to feedback from SNe and AGNs. As a consequence, gas-phase metallicity is a fundamental test for all models of galaxy formation.

A fundamental discovery has been the relation between stellar mass $M_\star$ (or luminosity) and metallicity (McClure & van den Bergh, 1968; Lequeux et al., 1979; Garnett, 2002; Lamareille et al., 2004; Pilyugin et al., 2004; Tremonti et al., 2004; Lee et al., 2006; Liang et al., 2006; Pilyugin & Thuan, 2007), with more massive galaxies showing higher metallicities. The origin of this relation is debated, and many different explanations have been proposed, including ejection of metal-enriched gas (e.g., Edmunds 1990; Tremonti et al. 2004), "downsizing", which is a systematic dependence of the efficiency of star formation on galaxy mass (e.g., Brooks et al. 2007; Mouhcine et al. 2008; Calura et al. 2009), variation of the IMF with galaxy mass (Köppen et al., 2007), and infall of metal-poor gas (Finlator & Davé, 2008; Davé et al., 2010).

The evolution of the luminosity-metallicity and mass-metallicity relations has been studied by many authors at z<1.5 (Contini et al., 2002; Kobulnicky et al., 2003; Maier et al., 2004; Liang et al., 2004; Kobulnicky & Kewley, 2004; Maier et al., 2005; Savaglio et al., 2005; Shapley et al., 2005; Lee et al., 2006; Lamareille et al., 2006; Maier et al., 2006; Liu et al., 2008;

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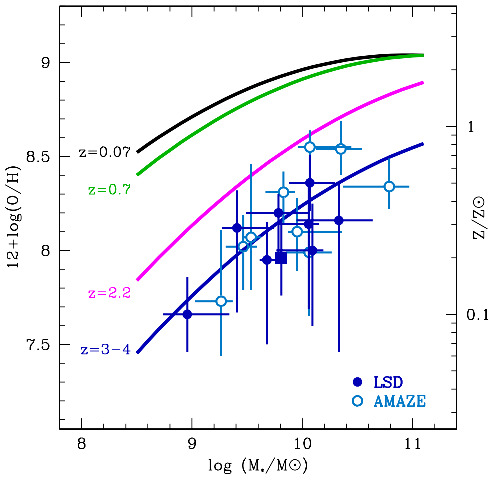

Fig. 1. Evolution of the mass-metallicity relation from local to high redshift galaxies from Mannucci et al. (2009). Data are from Kewley & Ellison (2008) (z=0.07), Savaglio et al. (2005) (z=0.7), Erb et al. (2006) (z=2.2) and Mannucci et al. (2009) (z=3–4).

Cowie & Barger, 2008; Rodrigues et al., 2008; Hayashi et al., 2009; Lara-López et al., 2009; Lamareille et al., 2009; Pérez-Montero et al., 2009; Queyrel et al., 2009; Vale Asari et al., 2009; Thuan et al., 2010; Zahid et al., 2011) at z∼2–3 (Erb et al., 2006; Hayashi et al., 2009; Yoshikawa et al., 2010; Richard et al., 2011), and at z>3 (Pettini et al., 2001; Maiolino et al., 2008; Mannucci et al., 2009; Lemoine-Busserolle et al., 2010), finding a strong and monotonic evolution, with metallicity decreasing with redshift at a given mass (see Fig.1). Both the shape and the normalization of the mass-metallicity relation are sensitive to the metallicity calibration used (Kewley & Ellison, 2008; Peeples & Shankar, 2011), which can differ significantly. Part of the differences is due to the secondary nature of nitrogen, whose abundance ratio with oxygen is expected and observed to vary during the galaxy lifetime. As several metallicity calibrations are based on the flux ratio of oxygen emission lines to the [NII]λ6584 line, this uncertainty also affects the oxygen abundance (e.g., Pilyugin et al. 2004; van Zee & Haynes 2006; Liang et al. 2006; Pérez-Montero & Contini 2009; Queyrel et al. 2009; López-Sánchez & Esteban 2010; Pilyugin & Thuan 2011; Thuan et al. 2010). This point will be addressed in a forthcoming paper (Maiolino et al., in preparation). Despite these problems, the evidence of evolution of the mass-metallicity relation is not affected by calibration uncertainties and is a very solid result.

Some authors (Erb et al., 2006; Erb, 2008; Mannucci et al., 2009) have studied the relation between metallicity and gas fraction, i.e., the effective yields. These results can be explained as a consequences of infall in high redshift galaxies. Also, Cresci et al. (2010) studied the metallicity maps of three star-forming galaxies at z>3, founding regions of low metallicity associated with the peak of star-formation. This evidence can be explained assuming that some metal-poor infalling gas both fuels star formation and dilutes metallicity. If infall is at the origin of the star formation activity, and outflows are produced by exploding supernovae (SNe), a relation between metallicity and SFR is likely to exist. In other words, SFR is a parameter that should be considered in the scaling relations that include metallicity.

2. A Fundamental Metallicity Relation in the local universe

In Mannucci et al. (2010) we studied the dependence of metallicity on both mass and SFR in SDSS galaxies. As shown in Fig.2, at constant stellar mass, metallicity anti-correlates with SFR, i.e., galaxies with higher SFRs also show lower metallicities. The dependence of metallicity on $M_\star$ and SFR can be better visualized in a 3D space with these three coordinates, as shown in Fig. 3. In this space, SDSS galaxies appear to define a tight surface, named the Fundamental Metallicity Relation (FMR). The introduction of the FMR results in a significant reduction of residual metallicity scatter with respect to the simple mass-metallicity relation. The dispersion of individual SDSS galaxies around the FMR is about ∼0.05 dex i.e, about 12%, and this scatter is consistent

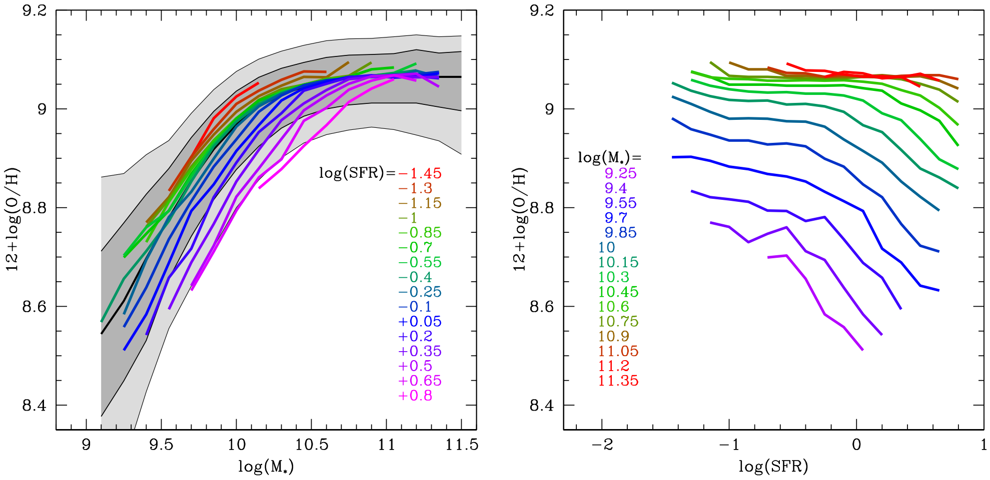

Fig. 2. *Left panel:* The mass-metallicity relation of local SDSS galaxies. The grey-shaded areas contain 64% and 90% of all SDSS galaxies, with the thick central line showing the median relation. This is very similar to what has been found by Tremonti et al. (2004), but the dispersion of our sample is somewhat smaller, 0.08dex instead of 0.1dex. The colored lines show the median metallicities, as a function of $M_\star$, of SDSS galaxies with different values of SFR. Metallicity shows a systematic decreas with increasing SFR. *Right panel:* median metallicity as a function of SFR for galaxies of different $M_\star$. At all $M_\star$ with log($M_\star$)<10.7, metallicity decreases with increasing SFR at constant mass .

with the intrinsic uncertainties in the measures of metallicity , mass, and SFR.

Mannucci et al. (2011) have extended this relation toward lower stellar masses, down to about $10^8 M_\odot$(see Fig.4).

The resulting FMR can be expressed by:

$$\begin{aligned} 12\ &+log(O/H) = \\ &= 8.90 + 0.37m - 0.14s - 0.19m^2 \\ &\quad + 0.12ms - 0.054s^2 \qquad \text{for } \mu_{0.32} \geq 9.5 \\ &= 8.93 + 0.51(\mu_{0.32} - 10) \quad \text{for } \mu_{0.32} < 9.5 \end{aligned} \tag{1}$$

where m=log($M_\star$)-10 and s=log(SFR) are in solar units, $\mu_{0.32} = log(M_\star) - 0.32 * log(SFR)$, and $8 < log(M_\star) < 11.5$ and $-1.5 < log(SFR) < 1.0$.

It is interesting to compare the metallicity properties of high redshift galaxies to the local FMR. In Mannucci et al. (2010) we did this computation using data from the literature and our sample of galaxies z>3. Astonishingly, we found no evolution up to z=2.5, i.e., high redshift, star-forming galaxies follow the same FMR defined by local SDSS galaxies, with no sign of evolution. This has been confirmed by Cresci et al (in preparation), who studied a large sample of galaxies at z~0.2 and z~0.6 from the zCosmos sample, obtaining no indication of evolution off the FMR.

This is an unexpected result, as simultaneously the mass-metallicity relation is observed to evolve rapidly with redshift (see Fig.1). The solution of this apparent paradox is that distant galaxies have, on average, larger SFRs, and, therefore, fall in different parts of the same FMR. Several recent studies (Richard et al., 2011; Erb et al., 2010; Nakajima et al., 2011; Trump et al., 2011; Contini et al., 2011; Atek et al., 2011) have presented samples of high-redshift galaxies whose SFRs are significantly higher or lower than most of the previously-known galaxies. In all these cases, a discrepancy with the mass-metallicity relation at that redshift is observed, together with a good agreement with the FMR. In this respect, the FMR has a real predictive power, i.e., the metallicity of a star-forming galaxy can be predicted at the 0.1dex level from its mass and SFR.

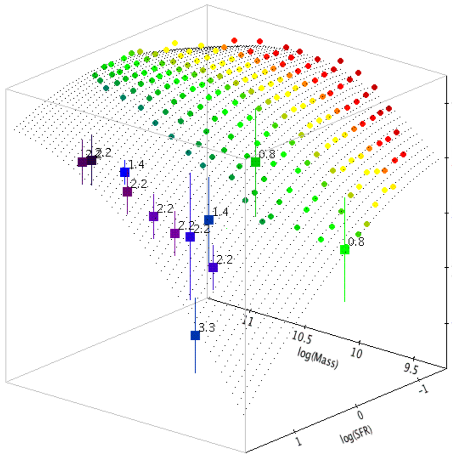

Fig. 3. The Fundamental Metallicity Relation plotted in the 3D space defined by $M_\star$, SFR and gas-phase metallicity. Circles without error bars are the median values of metallicity of local SDSS galaxies in bin of $M_\star$ and SFR, color-coded with SFR. The black dots show a second-order fit to these SDSS data, extrapolated toward higher SFR. Square dots with error bars are the median values of high redshift galaxies, as explained in the text. Labels show the corresponding redshifts. All the the high-redshift data, except the point at z=3.3, are found on the same surface defined by low-redshift data.

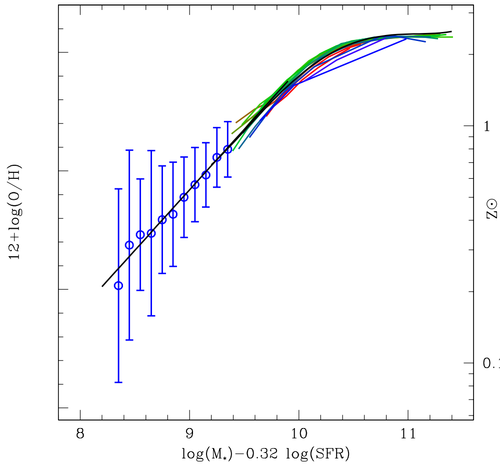

Fig. 4. Extension of the FMR towards low-mass galaxies, adapted from Mannucci et al. (2011). The blue dots show the median metallicity of low mass SDSS galaxies in bins of $\mu_{0.32}$ in solar units, as defined in Mannucci et al. (2010). The coloured lines are local SDSS galaxies from Mannucci et al. (2010), color-coded from red to blue according to increasing SFR. The black thick line shows the polynomial fit. For comparison, the black dotted line is the extrapolation of the 2nd degree fit to the FMR of the SDSS galaxies as defined in Mannucci et al. (2010) and plotted for SFR=0.

This no evolution is observed up to z∼2.5. Galaxies at z∼3.3 show metallicities lower of about 0.6 dex with respect to both the FMR defined by the SDSS sample and galaxies at 0.5<z<2.5. This is an indication that some evolution of the FMR appears at z>2.5, although its size can be affected by several potential biases (see Mannucci et al. 2010 for a full discussion). This result is confirmed by Sommariva et al. (in preparation) who studied the relation between mass and *stellar* metallicity in star-forming galaxies at z>3. They found a good agreement between stellar and gas-phase metallicities, confirming the evolution of the FMR.

Several authors are now using the FMR as an additional constraint for their models of galaxy formations and are proposing different ways to explain the existence of such a tight correlation (Mannucci et al., 2010; Campisi et al., 2011; Dib et al., 2011; Peeples & Shankar, 2011; Davé et al., 2011b,a). The actual physical significance of the FMR is not yet completely clear, but its explanation will probably involve some complex interaction between infalling metal-poor gas, outflowing metal-enriched gas, mass- and metallicity-dependent efficiency of star formation, and possibly systematic differences in the IMF.

3. The metallicity of GRB hosts

Recent studies on the final evolutionary stages of massive stars (Woosley & Heger, 2006; Fryer et al., 1999) have suggested that a Wolf-Rayet star can produce a long GRB if its mass loss rate is low, which is possible only if the metallicity of the star is lower than $\sim 0.1 - 0.3\,Z_\odot$. In this view, GRBs may occur preferentially in galaxies with low-metallicity

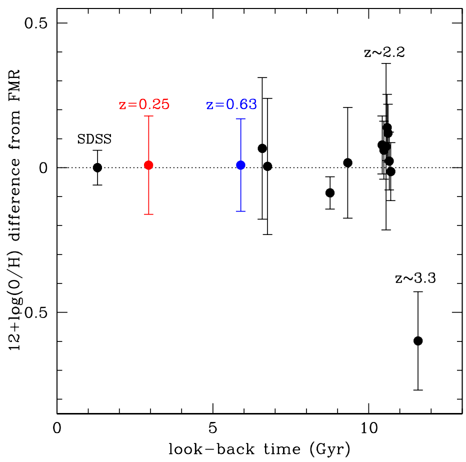

Fig. 5. Metallicity difference from the FMR for samples of galaxies at different redshifts, from Cresci et al. (in preparation). The black dots are the original data from Mannucci et al. (2010), the colored dots are zCosmos galaxies. The SDSS galaxies defining the relation are showing at z∼0.1 with their dispersion around the FMR. All the galaxy samples up to z=2.5 are consistent with no evolution of the FMR defined locally. Metallicities lower by ∼0.6 dex are observed at z∼3.3.

(Fynbo et al., 2003; Prochaska et al., 2004; Fruchter et al., 2006), even if low-metallicity progenitors can also be present in hosts with relatively high metallicities (Campisi et al., 2009).

Observationally, the role of metallicity in driving the GRB phenomena remains unclear and it is still debated (Fynbo et al., 2003; Prochaska et al., 2004; Fynbo et al., 2006; Wolf & Podsiadlowski, 2007; Price et al., 2007; Modjaz et al., 2008; Kocevski et al., 2009; Savaglio et al., 2009; Graham et al., 2009b,a; Levesque et al., 2010a,c,d; Svensson et al., 2010; Fan et al., 2010). Many recent studies have compared GRB hosts to the rest of the galaxies (see, for example, Fynbo et al. 2008). In particular, some of these studies have compared the observed mass-metallicity relation (or luminosity-metallicity relation) of the two populations, finding that long GRB host galaxies fall below the relation for the normal galaxy population, i.e., GRB hosts are less enriched in metals than the typical galaxies of the same stellar mass.

In order to check whether this bias exists, we have considered the properties of the GRB hosts in the light of the observed FMR. To this extent, we have collected all the GRB host galaxies at z<1 with available observations to measure, at the same time, stellar mass, SFR, and gas phase metallicity. Line fluxes of long GRB hosts have been published by several authors (Savaglio et al., 2009; Han et al., 2010; Levesque et al., 2010b). We have measured gas-phase metallicities by simultaneously considering all the flux ratios among the relevant emission lines, and using the calibration in Maiolino et al. (2008). Dust extinctions have been obtained using the Balmer decrement. SFR have been estimated from Hα corrected for extinction, using the calibration in Kennicutt (1998). Finally, stellar masses have been taken from Savaglio et al. (2009).

These data are plotted in fig. 6 and compared with both the mass-metallicity relation (left panel) and the FMR (right panel) of local SDSS galaxies. The comparison with the mass-metallicity relation shows that, as already obtained by Levesque et al. (2010b) and Han et al. (2010), GRB host galaxies have lower metallicity than galaxies of the same mass. In contrast, we also find that GRB hosts do follow the FMR and its extension towards low masses, without any significant discrepancy. In other words, when the dependence on SFR is properly taken into account, the metallicity properties of long GRB hosts do not differ substantially from those of the typical field population.

As a consequence, the typical low, subsolar metallicity found in many recent studies does not mean that GRBs occur in special, low-metallicity galaxies, but rather it is a consequence of the well-known link between the GRB event and the death of a massive stars, which produces a relation between long GRBs and star formation (Totani, 1997; Porciani & Madau, 2001). In the local universe, about 70% of all star formation activity occurs in galaxies with masses between $10^{9.5}$ and $10^{10.2}M_{\odot}$(Mobasher et al., 2009), where

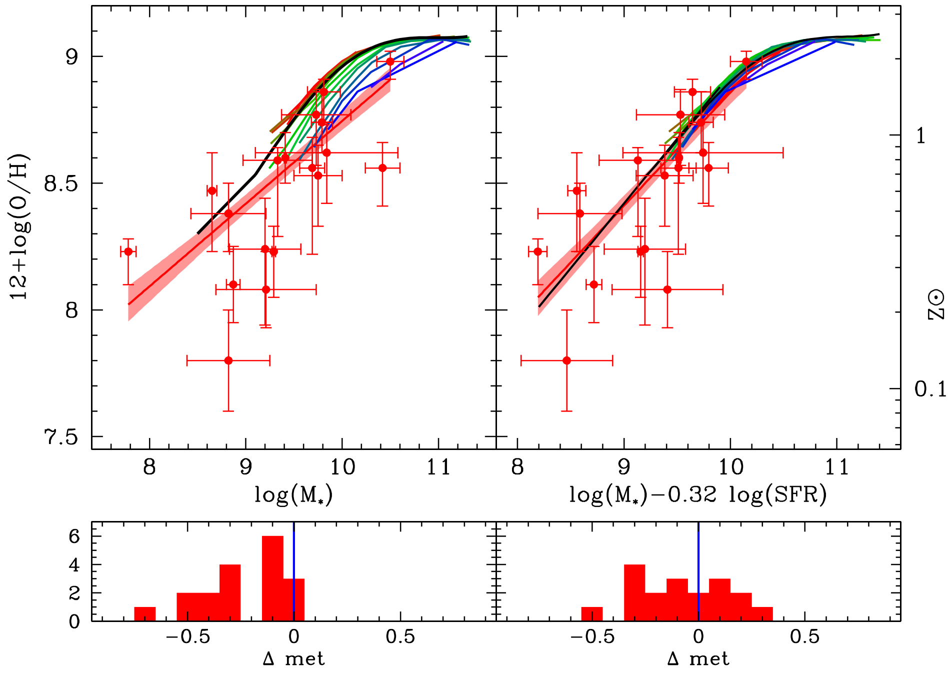

Fig. 6. Long-GRB hosts (red dots) are compared with the Mass-Metallicity relation (*left*) and the FMR (*right*) of local galaxies. Symbols are as in Fig.4. The red thick line is a linear fit to GRB host data, with $\pm 1\sigma$ bands shown in light red. The *lower panels* show the difference between the metallicity of the GRB hosts and mean relations of SDSS galaxies (black curves). It is clear that GRB host follow a different mass-metallicity relation and show systematically lower metallicities. In contrast, they are in perfect agreement with the predictions of the FMR. In other words, they have the metallicity that is expected based of their mass and SFR.

most of the GRB of our sample are also found. The low metallicities are a consequence of the low masses and of the high SFRs. It should be noted that our sample consists mostly of long GRBs whose position has been provided by the detection of their optical afterglow. It is known that a population of GRBs with a bright X-ray afterglow and lacking of optical counterparts does exist, the so-called dark GRBs, and most of them reside in dusty environments (e.g., Perley et al. 2009; Küpcü Yoldaş et al. 2010). It is possible that dark GRB hosts would populate the region of the FMR at high values of μ_α and metallicity.

Our results have an important implication for future studies of the high redshift universe. Given that GRB hosts appear to be normal, actively star-forming galaxies, large samples of GRB hosts can be used to study the FMR of normal starburst galaxies. This is particularly exciting since GRBs may allow to extend current studies of the FMR both toward low values of μ_α and toward higher redshift, in principle up to extremely high redshifts, at least up to $z \sim 8$ as shown by GRB 090423 (Salvaterra et al., 2009).

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